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Process Compensated Resonance Testing Modeling for Damage Evolution and Uncertainty Quantification

Eric Biedermann[2], Julieanne Heffernan[2], Alexander Mayes[2], Garrett Gatewood[2], Leanne Jauriqui[2], John C. Aldrin[3], Brent Goodlet[4], Tresa Pollock[4], Chris Torbet[4], J. Steve Cargill[5], Siamack Mazdiyasni[1], [1]Air Force Research Laboratory (AFRL/RXCA), Wright-Patterson AFB, OH 45433; [2]Vibrant Corp., Albuquerque, NM 87113, USA; [3]Computational Tools, Gurnee, IL 60031, USA; [4]University of California, Santa Barbara, Santa Barbara, CA 93106, USA; [5]Aerospace Structural Integrity, Inc., Hobe Sound, FL 33455, USA

Process Compensated Resonance Testing (PCRT) is a nondestructive evaluation method that measures and analyzes the resonance frequencies of a component for material state characterization, defect detection and process monitoring. PCRT inspections of gas turbine engine components have demonstrated the sensitivity of resonance frequencies to manufacturing defects and in-service thermal and mechanical damage. Prior work on PCRT modeling has developed forward modeling and model inversion techniques that simulate the effects of geometry variation, material property variation, and damage on Mar-M-247 nickel-based superalloy samples. Finite element method (FEM) forward model simulations predicted the effects of variation in geometry, material properties and damage on resonance frequencies. Model inversion used measured resonance frequencies to characterize the material state of components. Parallel work developed a process for uncertainty quantification (UQ) in PCRT models and measurements. The UQ process evaluated the propagation of uncertainty from various sources, identified the most significant uncertainty sources, and enabled uncertainty mitigation to improve model and measurement accuracy. Current efforts have expanded on those developments in several areas. One-factor-at-a-time (OFAT) forward model simulations were conducted on cylindrical dog bone coupons made from Mar-M-247. The simulations predicted the resonance frequency response to variation in geometry, elastic properties, crystallographic orientation, creep strain and cracking. The OFAT studies were followed by forward model Monte Carlo simulations that predicted the effects of multiple, concurrent sources of variation and damage on resonance frequencies, allowing characterization of virtual populations and quantification of uncertainty propagation. The Monte Carlo simulation design points were used to demonstrate the generation of a virtual database of components for training PCRT inspection applications, or "sorting modules." Virtual database training sets can potentially overcome the limitations imposed by the availability of components and material states for training sets based on physical examples. Forward modeling tools and techniques were applied to titanium to simulate the effects of material variation, damage, and crystallographic texture. Forward modeling was also applied to more complex geometries, including a notional turbine blade, to demonstrate the application of modeling tools to shapes representative of gas turbine engine components. Model inversion tools and techniques have also advanced under the current effort. Prior inversion methods relied on iterative fitting to polynomial expressions for simple geometries and bulk material properties. Current efforts have demonstrated FEM-based model inversion which allows characterization of complex shapes and material states. FEM-based design spaces were generated, model inversion was carried out for surrogate modeled resonance spectra, and inversion performance was evaluated. Analysis of PCRT modeling results led to the development of automated resonance mode matching tools based on the calculation of modal assurance criteria (MAC) values, mode shape displacement metrics and Hungarian Algorithm sorting methods.

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